Monolithic InGaAs/GaAs multi-QWs DFB nano-

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Abstract: Ultra-large-volume and low-cost-per-chip CMOS photonics integrated circuit has been searching for high-performance, Si-compatible laser sources that can be directly integrated on Si wafer for mass production. III-V semiconductor, the considered efficient light generation material, unfortunately has big lattice mismatch and thermal expansion contrast with Si, extremely difficult to be epitaxially grown on Si. Here we demonstrate an optically pumped monolithic InGaAs/GaAs multi-QWs single-mode DFB nano-ridge laser which is directly grown from 300 mm Si wafer by using aspect ratio defect trapping technique.

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1. Introduction

Photonics integrated circuit has attracted enormous investigations and investments, holding the potential of lower power consumption and higher transfer capacity compared with electronics integrated circuit. The potential of leveraging well-established CMOS manufacturing processes developed initially by the electronics industry has been the main driver fuelling massive research efforts into Si photonics over the last decade. Although considerable progress has been made in the field as a whole, the lack of a monolithically integrated laser on silicon remains a fundamental obstacle in further opening the field to a wider range of applications. Finding new ways to efficiently integrate direct bandgap III-V materials on silicon has therefore attracted considerable attention [1].

Integration methods relying on the bonding of GaAs or InP epitaxial layer onto silicon photonics circuits have been rather successful and allowed to demonstrated a wide variety of laser devices directly integrated with silicon photonics waveguides, including VCSELs, Fabry-Perot lasers, DFB (distributed feedback) lasers and micro-disk lasers [2]. However, it involves rather complex processing and it is not fully clear yet if these methods can be up scaled for mass production. Therefore we are investigating new approaches to integrate III-V semiconductors on silicon using epitaxy. In our earlier work [3] we demonstrated InP and InP/InGaAs DFB lasers grown on (001) silicon using a selective process. Here we report the first monolithic InGaAs/GaAs multi-quantum well (multi-QWs) nano-ridge lasers directly grown on a 300 mm Si wafer.

2. GaAs Epitaxy on Si

Given the large mismatch in lattice constant between silicon and most relevant III-V semiconductors, the quality of III-V materials directly grown on Si typically suffers from misfit and threading dislocations (TDs). The difference in thermal expansion coefficients between Si and III-V makes the situation even worse. Several approaches to overcome these issues have been reported in literature. Often the remaining misfit and threading dislocation density still limits device performance and lifetime however or non-selective processes are used. The novel approach to integrate GaAs on silicon we report here relies on aspect ratio trapping (ART) of defects in narrow oxide trenches to suppress threading dislocations [4]. In addition, the silicon at the bottom of the trenches is V-shaped such that III-V nucleation takes place on the {111} Si facets and the formation of anti-phase domains is avoided. When reaching the top surface of the oxide mask the GaAs growth is continued. Controlling the growth conditions allows to modify the shape of the resulting structure and to optimise it such that it can support a low-loss optical mode [5].

The ART technique is based on a standard shallow trench isolation (STI) process flow whereby trenches of 100 nm in width and 5 mm in length are patterned on a (001) Si substrate covered with a 300 nm thick SiO_2 layer. (Fig.1 (a)).

The V - shaped Si groove with exposed {111} facets is achieved by a tetramethylammonium hydroxide (TMAH) wet-etch step. The GaAs epitaxy is performed by metal-organic vapor phase epitaxy (MOVPE) in a 300 mm deposition chamber applying group-V and -III precursors such as tertiarybutyl arsine (TBAs), trimethyindium (TMIn), triethylgallium (TEGa) and trimethylgallium (TMGa). Three compressively strained InGaAs multi-QWs layers with around 20% Indium are embedded in the GaAs ridges as the active region (Fig.1 (b)). The growth process is completed by depositing a passivation layer of InGaP covering the full ridge (Fig.1 (c)). The thickness of the QW layers is about 12 nm and their position was optimized to achieve high optical confinement in the active region. The ridge waveguides are around 600 nm in height and 350 nm in width.

A Finite Difference Eigenmode (FDE) simulation at a wavelength 1030 nm(Fig.1 (d)) shows the basic TE mode is well guided in the GaAs ridge waveguide, exhibiting an effective index $n_{eff} = 3.14$, a confinement factor in the QWs active region $CF = 8.4\%$ and negligible leakage loss towards the Si substrate (< 5 dB/cm). Although other waveguide modes including the fundamental TM mode and higher-ordered TEM modes do exist in the ridge waveguide, their high leakage into the substrate and low confinement factor in the QWs should inhibit good laser performance, making the structure practically single mode. Therefore starting from this nano-ridge structure, we designed and fabricated single-mode DFB lasers incorporating a $\lambda/4$ phase shift section optimised for working with this 1^{st} TE mode.

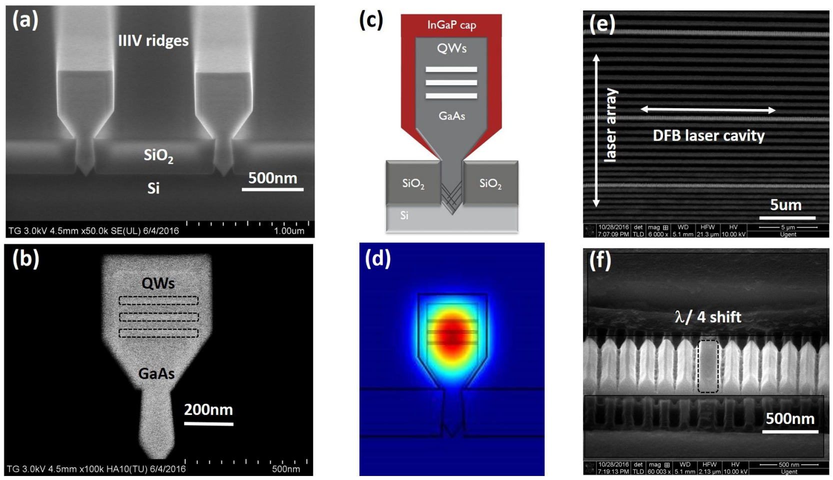

Fig. 1. **(a)** XSEM of InGaAs/GaAs QWs ridge waveguides array grown from trenches on Si substrate. **(b)** XSEM of the ridge structure, which shows the position of three InGaAs QWs. **(c)** The sketch of GaAs ridge waveguide, including 50 nm thick InGaP passivation layer. **(d)** Simulation of the 1^{st} TE mode guided in the structure. **(e)** SEM of DFB laser device array. DFB laser cavity is along horizontal direction. The image partly shows the gratings of three DFB devices in parallel. **(f)** SEM of the $\lambda/4$ shift section of a DFB laser.

3. DFB Laser

3.1. Fabrication

The DFB laser was realized by etching a 600 period gratings in the top surface of a GaAs ridge waveguide with a $\lambda/4$ shift in the middle (Fig. 1 (e),(f)). The grating period (165 nm) and depth (80 nm) were designed such that the 1^{st} TE mode Bragg stop band overlaps with the measured PL (photoluminescence) peak. In addition, a 50 period 2^{nd} order grating with period 330 nm was defined in the same GaAs ridge waveguide, 30 µm away from the DFB grating, to vertically couple out the laser light and allow characterisation of the devices in a standard micro-PL setup. As the 600 nm high GaAs waveguide array results in considerable surface topography, the sample was first planarized with a layer of 1.7 µm thick spin-coated BCB (Benzocyclobutene), and then etched back to the waveguide top surface. The gratings were patterned using electron-beam lithography (EBL) and inductive coupled plasma (ICP) etching with a $Cl_2/CH_4/Ar$ gas recipe. Fig. 1 (f) shows the fabricated gratings.

3.2. *Characterization*

The DFB lasers were characterized at room temperature using a micro-PL setup with a monochromator and an InGaAs detector. The pump source is a pulsed Nd:YAG laser with 7 ns pulse width and 1 kHz repetition rate operating at 532 nm. The pump intensity is controlled by a combination of a polarizer and a half-wave plate (HWP). Fig. 2 (a) shows the spectra of the DFB laser pumped at different intensities. When the pump power is below threshold, a broad PL spectrum is observed, centred at 1022 nm. As the pump power increases, a peak at 1028 nm appears in the spectrum. Finally, at a pump intensity of $110\,\mathrm{kW/cm^2}$ a single lasing peak reaches 25 dB above the background, demonstrating single mode laser performance. At a pump intensity of $150\,\mathrm{kW/cm^2}$ the full width at half maximum (FWHM) is 1.5 nm . Fig. 2 (b) plots the laser light-in light-out curve (L-L curve), both on a linear scale (Fig. 2 (b) insert) and on a logarithm scale, showing the typical features of laser operation. The threshold pump intensity is extracted to be $22\,\mathrm{kW/cm^2}$.

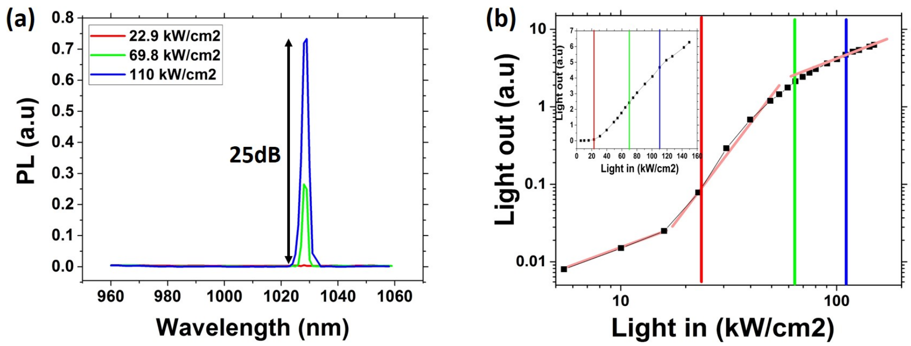

Fig. 2. **(a)** The measured DFB laser spectra under different intensities. A single lasing peak at 1028 nm appears when pump intensity is increased above threshold **(b)** L-L curve on logarithmic scale of the measured DFB nano-ridge laser (the insert is on linear scale.)

4. Summary

In this paper, we report the first GaAs/InGaAs multi-QWs single-mode DFB nano-ridge lasers directly grown on a 300 mm Si wafer. GaAs ridge waveguides with three InGaAs QWs sandwiched inside were grown on (001) Si substrates and optimized to have a low defect density, low optical leakage loss and high confinement in the active layers. A $\lambda/4$ shifted DFB-laser was designed and fabricated starting from this novel material. Room temperature measurement of the DFB-structure shows clear laser operation with 25 dB side mode suppression ratio at a wavelength of 1028 nm, a linewidth of 1.5 nm and a low threshold of $22\,\mathrm{kW/cm^2}$. This successful demonstration of a InGaAs/GaAs multi-QWs DFB nano-ridge laser directly grown on a 300 mm Si wafer proves the quality of the III-V epitaxial process and opens the road towards high volume manufacturing of silicon photonics ICs including laser and amplifier devices.

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References

1. D. Liang, J. Bowers "Recent progress in lasers on silicon," Nature Photonics 4, 511 (2010)
2. G. Roelkens, A. Abassi, P. Cardile, U. Dave, A. de Groote, Y. de Koninck, S. Dhoore, et al "III-V-on-Silicon Photonic Devices for Optical Communication and Sensing," Photonics. Vol. 2. No. 3. Multidisciplinary Digital Publishing Institute, 2015
3. Z. Wang, B. Tian,M. Pantouvaki, W. and Guo, P. Absil, J. Van Campenhout, C. Merckling, and D. Van Thourhout, "Room Temperature InP DFB Laser Array Directly Grown on (001) Silicon," Nature Photonics 9.12 (2015): 837-842
4. B. Kunert, W. Guo, Y. Mols, B. Tian, Z. Wang, Y. Shi, D. van Thourhout, J. Van Campenhout, R. Langer, K. Barla "III / V nano ridge structures for optical applications on patterned 300mm Silicon," Applied Physics Letters 109.9 (2016): 091101
5. B. Kunert, W. Guo, Y. Mols, R. Langer, K. Barla "Integration of III/V Hetero-Structures By Selective Area Growth on Si for Nano-and Optoelectronics," ECS Transactions, 2016, 75(8): 409-419